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SUMMARY OF PROJECT RULISON

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El Paso Natural Gas

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Austral Oil Company's interest in nuclear explosive stimulation of gas wells in the Rulison field began as early as 1965. The Company initially acquired approximately 20,000 acres, and, through additional leasing and farmout agreements, have increased their lease holdings to approximately 60,000 acres. Figure 1 is a map of the area.

The discovery well for the Rulison field was drilled in 1952, and up to the time of Austral's interest in 1965 seven wells had been drilled into the Mesaverde gas reservoir by other operators. In 1965-66 Austral drilled two test wells for the purpose of collecting data for a feasibility study.

The feasibility study, completed in 1966, indicated that nuclear explosives could possibly be applied economically as a method of stimulating production from the Mesaverde formation. The study also confirmed an estimated 90-125 Bcf of gas per square mile in the Rulison field.

The development of a technical plan was initially undertaken in 1967 with the Atomic Energy Commission's Lawrence Radiation Laboratory. In April 1968, the supporting laboratory was changed to Los Alamos Scientific Laboratory. The subsequent Project Definition Plan, and the implementation of that plan was accomplished with the Los Alamos Scientific Laboratory, the U. S. Bureau of Mines, and the AEC Nevada Operations Office. Austral also engaged the services of CER Geonuclear as consultant and Project Manager. Negotiations between the government and the industrial sponsors led to the signing of a contract on March 27, 1969 for the conduct of the experiment.

The stated objective of Project Rulison was "...to determine the potential of nuclear stimulation for the commercial development of the Rulison field." The conduct of the experiment was divided into three phases: (1) Determine site acceptability with regard to both reservoir characteristics and safety criteria; (2) Site construction and related activities associated with the nuclear detonation operations; and (3) Postshot investigations of reentry, ground motion effects, radioactivity, reservoir production, and economics.

An exploratory well was drilled to a depth of 8516 feet and completed in May of 1968. Some core samples and a suite of logs were taken in the Mesaverde section of the hole. Some sections above the Mesaverde were cored and tested for hydrological conditions. The ground water resources in the Rulison area are confined primarily to the near-surface alluvium and terrace deposits. The underlying bed rock formations are generally impermeable and yield little or no water.

The Mesaverde formation in the Rulison field area was deposited in the near-shore environment that included marine, flood plain and costal swamp conditions. This depositional setting resulted in lenticular sandstones which have limited aerial extent. This lenticularity is the primary cause of gas entrapment and retention in the Rulison field.

Average reservoir characteristics of the Mesaverde formation were determined preshot; first for the feasibility study and second from the Project Rulison exploratory well. Table 1 summarizes the findings.

Initially, May 22, 1969 was set for the Rulison shot date and by the first week of May the site was ready for the emplacement of the explosive. Some of the safety studies were not complete, however, and the shot was postponed to allow time for their completion.

During the summer, while the safety studies were being completed, the American Civil Liberties Union, the Colorado Open Space Coordinating Council and M. G. Dumond filed lawsuits to prevent the detonation of Project Rulison. The three separate lawsuits were combined into one suit which was then heard in the 10th U. S. District Court in Denver, Colorado under the jurisdiction of Judge Arraj. In this action the plaintiffs failed to obtain an injunction to stop the project. The case was then appealed to the U. S. Circuit Court of Appeals and to the Supreme Court without success. Although the injunction was denied, the Court maintained jurisdiction over the project and stipulated certain conditions and restrictions on the conduct of the project which required extraordinary equipment and procedures for reentry and production testing.

The incomplete safety questions concerned potential rock slides and the integrity of reservoirs in the area which could not be evaluated to the review bodies' satisfaction by the May 22 shot date. During the summer, after the completed studies indicated no problem of magnitude to forestall the project, work was resumed and September 4th was set as the readiness date. The explosive, supplied by the Los Alamos Scientific Laboratory, was contained in a canister about 9 inches in diameter and 20 feet long. It was emplaced to a depth of 8430 feet on a 3/4-inch cable. The hole was then stemmed with alternating sections of pea gravel and clay.

On September 4th the shot was ready, but the weather was not. For six days the shot was delayed because the weather conditions were not within the stringent restrictions. Many observers tired of the waiting and left before the shot. On the day of the shot, September 10th, there was still a

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moderate-sized crowd that showed up at the circus tent observer point near Grand Valley. Speeches were given and there was a small demonstration by sign-carrying opponents to the project. The leaders of the demonstration were also given time to talk from the stand. As the countdown continued, "hike-in" demonstrators were removed from the mountain near the project by helicopter and the speeches ended. Shortly after lunch the shot was fired and about three o'clock there was a press conference at the wellhead. There were no catastrophies. The day's excitement subsided and life resumed to near-normal as an afternoon rain shower sent people scurrying for cover. The yield of the explosion was 43 ± 8 kilotons.

The extreme precautions taken by the Atomic Energy Commission and the various review bodies to the project were very expensive; particularly to the industrial sponsors. Had the shot been fired in the spring, there probably would not have been the lawsuits. Had the weather restrictions been more realistic there would not have been the six-day delay to fire. These delays cost the industrial sponsors several hundred thousands of dollars. In a speech to the Atomic Industrial Forum (December 2, 1969), Austral's G. W. Frank said that, "By far the most expansive and expensive portion of Project Rulison is the Safety Program..." and that "Where Plowshare programs are concerned, this procedure certainly needs to be changed so the industrial sponsor can have some assurance that there will be no costly delays."

After reentry to the region near the chimney, production testing was started on October 4, 1970. A series of drawdown and shut-in tests were conducted until September 27, 1971. As the testing progressed, Austral retained the services of DeGolyer and MacNaughton (Dallas, Texas) to analyze and interpret the reservoir test data. The test data obtained was also placed in the Plowshare open file which made it available to anybody that wanted it. It is believed that several other companies interested in nuclear stimulation obtained the data from the open file and made their own proprietary analyses.

Analysis of the test data indicated that the void volume of the chimney was about 1.5 million cubic feet. This is consistent with a rubble-filled chimney of about 74 feet radius and 350 feet above the shot point. The height of the chimney could not be measured directly, but a reasonably good estimate was made from re-entry drilling observations and later Krypton-85 data. The analysis of water production data and its relation to high pressure vaporization temperatures indicated a chimney temperature of 445°F at the time of the flow tests between October 1970 and April 1971. The temperature of the unstimulated rock at the shot depth is about 214°F.

There were four intermittent flow periods included in the testing program. The first flow test was at high rate (2-6 million cubic feet per day) to provide a sample for the safety people to "calibrate" their off-site surveillance program for the test program to follow. The following three tests were for the purpose of obtaining data for a reservoir engineering analysis. Approximately 455 million cubic feet of gas, including dilutants, was produced in these tests.

Just prior to the first test a gas pressure of 3150 psig was recorded at a depth of 8200 feet. Throughout the flow tests radioactivity was measured on-line as well as samples taken periodically for laboratory analysis. In the early part of the flow tests the gas composition was approximately 33% methane, 45% carbon dioxide, 16% hydrogen and 6% other constituents. About 15,000 barrels of water were

TABLE I

RESERVOIR PROPERTIES DETERMINED PRESHOT

	FEASIBILITY Study	EXPLORATORY Well	FLOW Test
Porosity (%)	9.7	7.8 - 8.7	
Permeability (Md)	0.5	11*	.008
Gas Saturation (%)	54	45 - 62	
Water Saturation (%)	45	38 - 55	
Oil Saturation (%)	1	1	
Temperature @ 8400 feet (°F)		214	
Net Sand (feet)	500**	375***	
Gas in Place (Bcf/sq mile)	90 - 125	110	
Pressure (Psi)			2936

*from core tests
**net sand over entire Mesaverde section
***net sand over interval between 7302 and 8464 feet

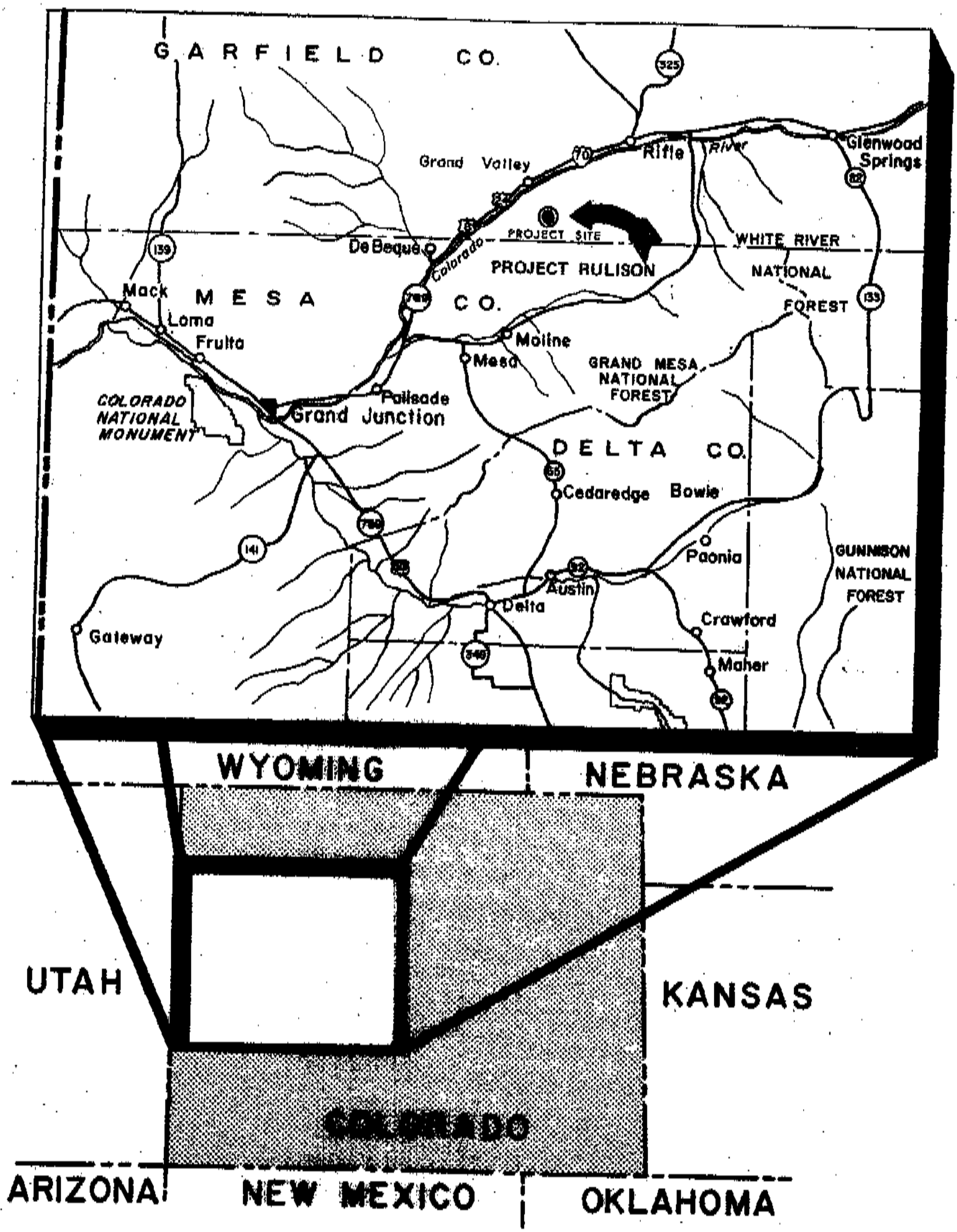

FIGURE 1. Map showing location of Project Rulison.

recovered at the surface during the tests. In addition, it was calculated that approximately 6,000 barrels of water was produced as vapor. It has been estimated that the chimney may have contained as much as 30,000 barrels to start with. This water was disposed of by injection into the flare.

For most of the flow tests the hydrogen and carbon dioxide concentrations declined essentially at the same percentage rate. The concentration of water vapor generally increased as the pressure in the chimney decreased. At the end of the tests there were approximately 170 barrels of water produced with each thousand cubic feet of gas. Towards the end of the tests, the percentage of carbon dioxide began to increase gradually from a minimum of 19% to approximately 22%. This has been interpreted as carbon dioxide evolution into the chimney either from decomposition of carbonate minerals or release of the gas which was dissolved in water. Laboratory measurements of the relative concentration of Carbon-14 in the gas have shown that carbon dioxide was initially formed at the time of the detonation, but was also generated by heating the rock subsequent to the detonation. The latter evolving carbon dioxide is free of Carbon-14. A total of 24 million standard cubic feet of carbon dioxide was estimated to have been evolved during the flow tests.

Preshot, the AEC stated that the particular explosive used at Rulison should leave about 10,000 curies of Tritium (about 1 gm). Krypton-85 would be generated at the rate of 1113 curies per kiloton. Only 2824 curies of Tritium and 1064 curies of Krypton-85 were produced during the testing period. Analysis of the Krypton-85 data was instrumental in determining the actual yield of the explosive. The whereabouts of the Tritium between the 10,000 curies predicted and the 2824 curies produced is not fully known. A total accounting of the Tritium could not be made. This was due in part to the unknown amount of water remaining in the chimney at the end of the flow tests and the uncertainty in the effectiveness of the boron carbide radiation shield that was placed around the device.

Since Rulison was not a conventional well completion, the conventional reservoir engineering analysis techniques could not be applied. Instead, matching of experimental data to computer simulation was employed. This technique is essentially that of selecting a set of reservoir characteristics, making the calculation and comparing the computed results to the experimental data. If the match is not good, a new set of parameters is fed to the computer and new results obtained. The parameters that give a reasonable match to the data can then be used in subsequent calculations to predict future production.

There are so many variables in the calculations and such a limited amount of test data it is not possible to obtain an explicite or unique determination of the reservoir properties for the chimney and surrounding region from either the test data or the computer simulation. The best that can be achieved is a consistent set of values that seem reasonable. For Rulison, results of computer matching were reported by Lawrence Livermore Laboratory (LLL) and DeGolyer and MacNaughton (D&M). At LLL the philosophy was to use as simple a model as possible consistent with making a reasonable computer match to the available experimental data. At D&M a more complex computer model was used which included the effects of water vaporization and carbon dioxide generation in the chimney, change of gas properties with temperature and pressure and a varying permeability in the fractured zone.

There was a significant difference in the approach taken to obtain an agreeable fit to the data between the two computations. At LLL the experimental flow rate was used to drive the computer model and pressures were calculated and compared to the data. At D&M and their subcontractor, Computer Technical Services, Inc., both pressures and flow were used to drive the computer calculation and permeability was adjusted to whatever value was required to find a reasonable fit to the data.

The parameters used by LLL to obtain a reasonable fit to the data are given in Table II. It was not necessary to

TABLE II

PARAMETERS USED AT LLL TO OBTAIN COMPUTER FIT TO DATA

Chimney temperature	400°F
Formation temperature	220°F
Formation gas gravity	0 - 65
Formation gas pressure	3200 psi
Chimney radius	76 feet
Permeability - height(76-207 ft.) (kh)	22.4 Md-ft
(207 + feet)	0.68 Md-ft
Porosity - height (ϕh)	3.0 feet

chimney-cracked k. If you also used 75', this gives 0.3 md for k in the nuclear stimulated zone

- far field k, this paper uses h of 75' to get a k of 0.009 md know the height, or net sand thickness for this simple approach; only the kh and h product terms were needed. For a net h of 75 feet then the in-situ permeability is about 0.009 md. This value is in good agreement with that from the flow test data given in Table I.

The parameters used at DeGolyer and MacNaughton to obtain a fit are given in Table III. As seen in Table III it was necessary to use fractured zone permeabilities ranging from .001 to .04 md to obtain a fit to the data. This variable permeability has been explained by the proponents of this model as being suggestive that the fracture zone was being cleaned of water as the well was produced. This explanation is not needed for the LLL model.

The analyses indicate that for the time of the tests the effective drainage radius did not reach much beyond the fracture radius. For long-term productivity, however, the drainage goes beyond this and the flow will be largely controlled by the matrix permeability. The future prediction of the two computer models are vastly different even though they both show a fit to the available data. The LLL model says the future production will be controlled by reservoir sand with an effective permeability of about .009 md. The DeGolyer and MacNaughton model, on the other hand, says that the controlling permeability will be .04 md. The LLL model predicts about 2 billion cubic feet production in 25 years while the DeGolyer and MacNaughton prediction is 5-7 billion cubic feet in 25 years.

At Austral's request, DeGolyer and MacNaughton made a preliminary reserve appraisal of the Rulison field based upon the results of Project Rulison. They found that if a much larger vertical section of the Mesaverde formation were to be stimulated with multiple explosives (4-6) in a single wellbore, then some 2 trillion standard cubic feet of natural gas reserves could be recovered by nuclear stimulation. If the overall cost of a completed well is within $1,000,000, then it should be economic at the current area rate price of 23.75¢/Mcf. This assumes a discounted annual return on investment of 20%.

TABLE III

PARAMETERS USED AT DeGLOYER & MacNAUGHTON TO FIT THE DATA

Cavity radius	74 feet
Cavity height	270 feet
Outer fracture radius	220 feet
Pay thickness	75 feet
Porosity	7.1%

Temperature .... 445°F in cavity and decreased proportionally to the logarithm of the radius to a value of 214°F at the outer fracture radius. Constant 214°F beyond the fracture radius.

Permeability of Fracture Zone (Md)

Outer Radius	1 - 30 Days	31 - 58 Days	59 - 68 Days	69 - 120 Days	120 - 359 Days	Postulated Ultimate
88	.1	.3	.3	.3	.3	.3
107	.01	.15	.17	.26	.26	.261
129	.001	.021	.06	.14	.22	.219
156	.001	.006	.02	.05	.16	.165
187	.001	.001	.002	.006	.015	.098
220	.001	.001	.001	.001	.001	.040
Average	.019	.0798	.0922	.1262	.1581	.1805